Particle Acceleration in the M87 Jet

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Abstract

The wealth of high quality data now available on the M87 jet inspired us to carry out a detailed analysis of the plasma physical conditions in the jet. In a companion paper (Lobanov, Hardee & Eilek, this proceedings) we identify a double-helix structure within the jet, and apply Kelvin-Helmholtz stability analysis to determine the physical state of the jet plasma. In this paper we treat the jet as a test case for *in situ* particle acceleration. We find that plasma turbulence is likely to exist at levels which can maintain the energy of electrons radiating in the radio to optical range, consistent with the broadband spectrum of the jet.

1 Introduction

We know a great deal about the jet in M87. Radio (10) and optical (11) images reveal ordered, filamentary structures whose synchrotron emission extends from radio at least to optical frequencies, and probably up to X-rays (8). Multi-epoch studies detect relativistic proper motion, at γ of a few(1).

The jet begins by expanding uniformly, out to ~ 2 kpc (we assume an angle $\sim 40^\circ$ to the line of sight, and a distance of 17 Mpc). At that point, the location of the bright knot A, it recollimates, and continues for another 1-2 kpc before disrupting strongly and depositing its matter and energy in the larger radio halo. The minimum pressure required to produce the synchrotron emission remains approximately constant during the expansion. Because p_{min} measures the energy density in relativistic electrons and magnetic field, $p_{min} \propto u_e^{4/7} u_B^{3/7}$, we know that these quantities do not decay adiabatically during the expansion. This is clear evidence that *in situ* energization is occuring.

The broadband, slice-integrated synchrotron spectrum is nearly constant along the jet. This suggests that the electron energy distribution is also nearly constant along the jet, and supports the idea that it is maintained against losses

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by *in situ* energization. We must recall, however, that the jet is not internally homogeneous. The radio-bright filaments probably show us high-field regions. In addition, resolved two-dimensional images show that the optical knots are more concentrated than the radio knots.

We have enough information about this jet to justify detailed modelling of the turbulence and its effect on the particles. To be specific, we consider particle acceleration by Alfvenic turbulence. In this paper we summarize our analysis, which will be published elsewhere in more detailed form.

2 Physical picture of the jet

From the radio and optical data we determine the overall physical state of the jet. In a companion paper (7) we show that the jet has an underlying double helix structure, which can be traced in radio and optical emissivity from the jet origin out to and past knot A. The structure of the helical filaments is consistent with elliptical and helical normal modes, which could be excited by the Kelvin-Helmholtz (KH) instability. Some of the bright "knots" in the jet are the points where the two filaments rotate into the line of sight. Other bright regions are superimposed on this pattern, such as the inner knots D and F, and the more ordered complex at and beyond knot A. We think knot A is a shock, connected to the recollimation of the jet, with emissivity enhanced by shear-driven turbulence. Past knot A the helical mode grows to large amplitudes, creating the distortions which ultimately disrupt the flow.

We emphasize that the jet is not axisymmetric, despite the very well defined apparent "edges" to the flow inside of knot A. From the structure of the excited modes (4), we know the plasma has localized high-pressure regions, close to the surface, which rotate through a helical pattern going along the jet. We propose that these regions, and other randomly placed local bright spots, are regions of enhanced, shear-driven MHD turbulence. We further speculate that this turbulence accelerates relativistic particles *in situ*, creating the radio and optical knots in the jet.

We can combine standard minimum-pressure analysis and KH stability analysis to estimate physical parameters within the jet. From the former (10, e.g.), we scale to $B \sim 100\mu$G, and $p \sim 10^{-9}$dyn/cm^2. From stability analysis (7), we estimate the internal Mach number of the jet to be a few, and the specific enthalpy of the jet plasma to be $h = \Gamma p/(\Gamma - 1)\rho c^2 \sim 1$. Thus, the jet cannot contain only highly relativistic plasma, and must have total $p > p_{min}$.

The jet must be in pressure balance with its surroundings in order to apply KH analysis. This means that the inner few kpc of the Virgo core [which contain the inner radio lobes (5) and the complex X-ray-loud plasma (13)] must be at a higher pressure than earlier, low-resolution X-ray work suggested. This is consistent with the dynamic appearance of the central region (13; 9). It is also consistent with the jet power, which we know is at least 3×10^{44}erg/s (9), and significant to the energy budget of the Virgo core.

3 Jet deceleration and plasma turbulence

We model the bright knots as localized sites of Alfvenic turbulence. This turbulence will accelerate relativistic particles. It will also trap the newly energized particles, so that they must diffuse away from the hot spots. The observation that the radio knots are more extended than the optical knots can be explained if the diffusion time, τ_{diff}, is comparable to the optical synchrotron loss time, $\tau_{sy,o}$.

We begin by determining the turbulence level necessary to contain the optically loud electrons. Let $\delta B^2/8\pi$ be the energy density in MHD turbulence, and let the turbulence have a characteristic (outer) scale λ_t. We follow (3) and estimate the cross-field diffusion coefficient $D_o \sim (c\lambda_t/3)\delta B^2/B^2$. We scale both the hot spot size and the turbulent scale to 10 pc. With these scalings, we estimate $\tau_{diff} \sim \tau_{sy,o}$ if $\delta B^2/B^2 \sim 0.1$.

Is this a reasonable turbulence level for the M87 jet? If the turbulence is driven by shear instabilities, the energy must come from the jet power, $P_j = \dot{M}\gamma_j c^2 \,(1+h)$ (where $\dot{M}$ is the mass flux). As friction and velocity shear decelerate the jet, energy is lost at a rate dP_j/dz. We assume a fraction ϵ of this goes to drive the turbulence; the rest goes directly to heating the jet and ambient plasmas. The most important damping mechanism in this situation is jet expansion (which "adiabatically" damps the turbulence). Balancing this against the driving, with jet deceleration $d\gamma/dz \sim 1/\mathrm{kpc}$, we find a very modest $\epsilon \sim .01$ can produce the required level of turbulence. We further note that wave-wave interactions, which modulate the turbulent spectrum and generate dissipative modes, probably set in at $\delta B^2/B^2 \sim 0.1$ (12, e.g.). This also agrees with our estimate above.

4 Impact on relativistic particles

We next ask whether this turbulence level can accelerate the electrons. Alfven wave acceleration proceeds *via* the cyclotron resonance, which requires the wavelength and particle energy to match, as $\gamma/\lambda \simeq eB/2\pi mc^2$. Very small scales are involved: wavelengths $\lambda \sim 10^{11}$ to 10^{14} cm resonate with radio-loud ($\gamma \sim 10^4$) to X-ray loud ($\gamma \sim 10^7$) electrons. The acceleration rate is determined by the turbulent energy at resonant scales. We expect turbulent power to cascade to smaller scales, but the resultant wavenumber spectrum, $W(k)$, is hard to predict. We follow tradition by assuming $W(k) \propto k^{-m}$, with total energy $\delta B^2/8\pi = \int W(k)dk$. Stochastic acceleration is described by a Fokker-Planck equation; quasi-linear theory can be used to find the momentum diffusion coefficient D_p, and from that $\tau_{acc} \sim p^2/D_p \propto \gamma^{2-m}$ (2, e.g.).

Can such turbulent acceleration offset radiative losses in the M87 jet? Do the accelerated particles produce a synchrotron spectrum like that observed? We have only begun this calculation. Our preliminary work suggests that wave spectra with $m \simeq 3/2$, which is typical of MHD turbulence in other settings (6), will offset synchrotron losses for electrons radiating at and below the optical range. This is pleasing, because it seems consistent with the observed synchrotron spectrum, which curves slowly between the radio to the optical, then steepens further while continuing to X-rays(10; 8).

Our simple estimates must be extended before they can usefully be tested against the data. The particle energy distribution must be determined, and convolved with the magnetic field structure in the jet, in order to predict a synchrotron spectrum which can be compared to observations. We are in the midst of those calculations, and will report their results in a future paper.

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